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13 March 2020

Version of attached file:

Published Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Smith, Russell J (2020) 'Discovering novae in early-type galaxies with MUSE : a chance find in NGC1404, and 12 more candidates from an archival search.', Monthly notices of the Royal Astronomical Society : letters., 494 (1). L1-L5.

Further information on publisher's website:

<https://doi.org/10.1093/mnrasl/slaa023>

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Discovering novae in early-type galaxies with MUSE: A chance find in NGC 1404, and 12 more candidates from an archival search

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Accepted 2020 February 3. Received 2020 January 31; in original form 2020 January 22

ABSTRACT

I report the discovery of a transient broad- $H\alpha$ point source in the outskirts of the giant elliptical galaxy NGC 1404, discovered in archival observations taken with the Multi-Unit Spectroscopic Explorer (MUSE) integral field spectrograph. The $H\alpha$ line width of 1950 km s^{-1} full width at half-maximum, and luminosity of $(4.1 \pm 0.1) \times 10^{36} \text{ erg s}^{-1}$, are consistent with a nova outburst, and the source is not visible in MUSE data obtained 9 months later. A transient soft X-ray source was detected at the same position (within $<1 \text{ arcsec}$), 14 yr before the $H\alpha$ transient. If the X-ray and $H\alpha$ emission are from the same object, the source may be a short-time-scale recurrent nova with a massive white dwarf accretor, and hence a possible Type-Ia supernova progenitor. Selecting broad- $H\alpha$ point sources in MUSE archival observations for a set of nearby early-type galaxies, I discovered 12 more nova candidates with similar properties to the NGC 1404 source, including five in NGC 1380 and four in NGC 4365. Multi-epoch data are available for four of these twelve sources; all four are confirmed to be transient on $\sim 1 \text{ yr}$ time-scales, supporting their identification as novae.

Key words: novae, cataclysmic variables – galaxies: elliptical and lenticular, cD.

1 INTRODUCTION

Nova eruptions are caused by thermonuclear detonation of material accreted on to the surface of a white dwarf (WD) from a companion star (see Bode & Evans 2008, for extensive reviews). The outburst expels part of the accreted envelope, but does not destroy the system, so it is thought that novae are inherently recurrent, though relatively few have undergone multiple recorded eruptions (~ 30 in the Milky Way, M31, and the Large Magellanic Cloud; see e.g. Darnley & Henze 2019). If these episodes lead to net growth in the WD mass (Hillman et al. 2016), then novae are important as a class of potential progenitors for Type-Ia supernovae.

Novae were historically considered promising as extragalactic distance indicators, leading to several systematic searches in galaxies beyond the Local Group, including early-type targets (Della Valle & Gilmozzi 2002; Ferrarese, Côté & Jordán 2003; Neill, Shara & Oegerle 2005; Curtin et al. 2015; Shara et al. 2016). While the classical decline-rate versus peak luminosity relation no longer seems viable as a distance indicator (e.g. Shara et al. 2017), the rate of nova production in early-type galaxies is also of interest, as a probe of close binary stars in stellar populations different than those in the Milky Way. Ground-based studies have typically reported luminosity-normalized nova rates of $\nu_K \sim (1-3) \text{ yr}^{-1} (10^{10} L_{\odot,K})^{-1}$ (e.g. Ferrarese et al. 2003; Curtin et al. 2015). Population synthesis models suggest that ν_K should be

larger for younger populations (Chen et al. 2016), but observed differences between spirals and ellipticals appear to be modest, and the bulges of M31 and M81 seem to exhibit larger ν_K than their discs (Ciardullo et al. 1987; Neill & Shara 2004; Darnley et al. 2006). The true total nova rate may be considerably higher; Shara et al. (2016) reported $\nu_K \approx 8 \text{ yr}^{-1} (10^{10} L_{\odot,K})^{-1}$, from densely time-sampled *Hubble Space Telescope* observations of M87, and suggested that classical searches missed fast-evolving novae, and those close to galaxy centres.

In the initial period after maximum light, the $H\alpha$ emission from a nova fades much more slowly than the optical continuum (Ciardullo, Ford & Jacoby 1983). The longer visibility time in $H\alpha$ has long been exploited in narrow-band photometric searches for extragalactic novae (e.g. Ciardullo et al. 1990a), typically using fixed narrow-band filters of $\sim 75 \text{ \AA}$ width. In general, wide-field integral-field spectroscopy (IFS) provides a more flexible approach to detecting emission-line sources, by matching the wavelength range to the width of the features being sought. Moreover, IFS data provide the full spectroscopic coverage simultaneously with the search process, which is not available from fixed- or tunable-filter observations. The only example of this approach so far is by Martin, Drissen & Melchior (2018), who detected five M31 novae in $H\alpha$, using single-epoch imaging Fourier-transform spectrometer observations.

In this Letter, I describe how novae can be identified at distances of $\sim 20 \text{ Mpc}$, using the more orthodox Multi-Unit Spectroscopic Explorer (MUSE) IFS on the ESO Very Large Telescope (Bacon et al. 2010). The work was prompted by the chance discovery of a

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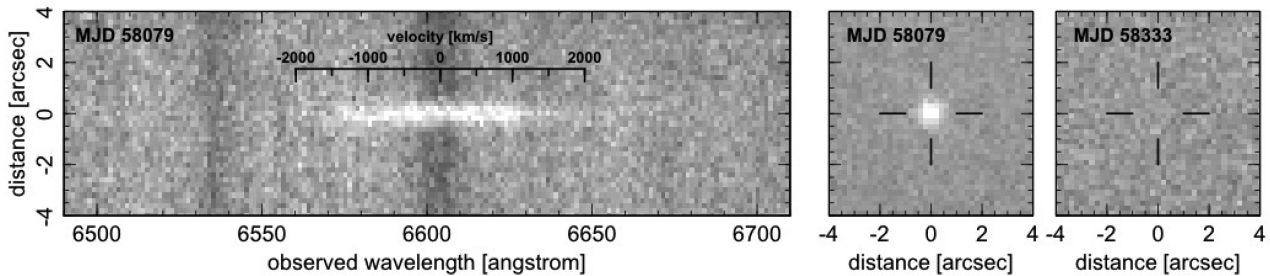


Figure 1. Left-hand panel: Two-dimensional spectrum of NGC 1404-S1 from MUSE, in a similar format to that used in discovering the source. Effectively this is a spectrum from a pseudo-slit of width 1 arcsec centred on the source, 37 arcsec from the galaxy centre. The narrow H α absorption line from the nearly uniform diffuse light of the galaxy is seen as the dark vertical band, while the much broader point source emission appears as the bright horizontal streak. Right-hand panels: Continuum-subtracted H α images of the source in the discovery data, and in a second epoch observation 254 d later.

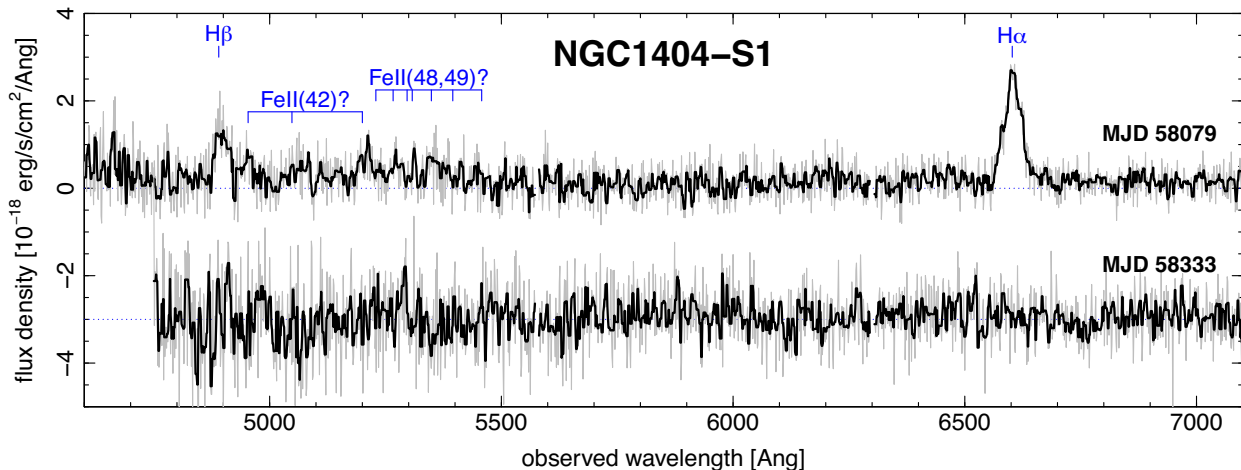


Figure 2. Extracted spectrum of NGC 1404-S1, after subtracting the diffuse background, showing the H α and H β emission lines in the discovery epoch spectrum (above) and the absence of emission in the later epoch (below, offset by 3×10^{-18} erg s⁻¹ cm⁻²). The grey trace shows the original spectrum, while the black trace includes a 5-pixel (6.25 Å) median smoothing. No lines are detected in NGC 1404-S1 beyond the spectral range shown.

transient H α source in NGC 1404, with properties consistent with a nova, as summarized in Section 2. Section 3 notes a spatially coincident transient X-ray source, detected more than a decade earlier than the H α detection, suggesting this nova is a recurrent system. Motivated by the NGC 1404 discovery, Section 4 describes a search for further novae in archival MUSE observations of nearby early-type galaxies, from which 12 more candidates are presented. Section 5 summarizes the work, highlighting the feasibility of a dedicated extragalactic nova survey with MUSE.

2 A TRANSIENT BROAD-H α SOURCE IN NGC 1404

The source described in this section, hereafter NGC 1404-S1, was discovered serendipitously during visual inspection of MUSE data for NGC 1404, a massive elliptical galaxy in the Fornax Cluster. The observation was obtained on 2017 Nov 22 (MJD 58079) for programme 296.B-5054, ‘The Fornax3D Survey’ (Sarzi et al. 2018). The total exposure time is 3600 s, the point spread function full width at half-maximum (FWHM) is ~ 0.7 arcsec, and the data were obtained on a photometrically stable night.

Viewing the archived data-cube in ‘pseudo-slit’ format, i.e. with one spatial and one spectral dimension, and scanning across the second spatial direction, revealed a striking broad emission feature centred on the much narrower stellar H α absorption line,

as reproduced in Fig. 1. The emission line is spatially unresolved, and projected 37 arcsec (3.6 kpc) from centre of NGC 1404, approximately twice the half-light radius (Jarrett et al. 2003). After extracting a one-dimensional spectrum, and subtracting the local background, a corresponding H β line is also visible, confirming the source as being associated with NGC 1404, rather than an active galactic nucleus in the background (Fig. 2). The H α luminosity is $(4.1 \pm 0.1) \times 10^{36}$ erg s⁻¹, while the line width is 1950 km s⁻¹ FWHM. The position of NGC 1404-S1 is covered by another MUSE observation, obtained on 2018 Aug 03 (MJD 58333). NGC 1404-S1 is undetected in this second-epoch observation, with continuum and line emission consistent with zero.

The most plausible interpretation of NGC 1404-S1 is as a nova. The luminosity is consistent with the characteristic peak output of novae (10^{36-37} erg s⁻¹ at maximum; Ciardullo et al. 1990b), and linewidths of ~ 2000 km s⁻¹ are also typical (e.g. Shafter et al. 2011). Given the H α luminosity, the typical continuum-to-line flux ratios for novae $\gtrsim 15$ d after maximum (converted from B -H $\alpha \approx 2.7$ in the system of Ciardullo et al. 1990a) correspond to an expected B -band continuum flux of $\sim 3 \times 10^{-19}$ erg s⁻¹ cm⁻² Å⁻¹, which is compatible with the measured signal at the blue end of the MUSE spectrum ($2.6 \pm 0.05 \times 10^{-19}$ erg s⁻¹ cm⁻² Å⁻¹). The disappearance of the source after 254 d is expected for typical nova H α decline rates. The Balmer decrement in novae is commonly steeper than for the standard Case-B recombination ratios, with

Table 1. Candidate novae detected in MUSE observations of nearby early-type galaxies. MJD is the Modified Julian Date for the discovery observation epoch, or the time difference from discovery for other epochs. The $H\alpha$ FWHM is determined from a simple Gaussian fit to the discovery epoch spectrum. The line fluxes are measured within an aperture of diameter 1.2 arcsec, and ± 1.06 FWHM, i.e. $\pm 2.5 \sigma$. The adopted distances are from Tonry et al. (2001) for NGC 584, and Blakeslee et al. (2009) for the other galaxies. The candidates from Section 4 are ordered by host-galaxy RA and $H\alpha$ significance.

Host	Distance (Mpc)	Source	RA (J2000)	Dec.	$H\alpha$ FWHM (km s ⁻¹)	MJD (d)	Flux (10 ⁻¹⁷ erg s ⁻¹ cm ⁻²)	Luminosity (10 ³⁶ erg s ⁻¹)
NGC 1404	20.2	S1	03:38:51.54	-35:35:01.5	1947	58079	8.40 \pm 0.23	4.10 \pm 0.11
						+ 254	0.17 \pm 0.43	0.08 \pm 0.21
NGC 584	20.1	S1	01:31:18.28	-06:52:37.0	1433	57570	2.87 \pm 0.45	1.39 \pm 0.22
NGC 1380	21.2	S1	03:36:29.61	-34:57:35.2	1023	57773	3.12 \pm 0.18	1.68 \pm 0.10
						+ 294	-0.07 \pm 0.18	-0.04 \pm 0.10
		S2	03:36:29.47	-34:57:57.2	1568	57773	2.90 \pm 0.25	1.56 \pm 0.13
						+ 294	-0.74 \pm 0.34	-0.40 \pm 0.18
		S3	03:36:28.55	-34:58:57.0	2110	57753	3.37 \pm 0.41	1.81 \pm 0.22
		S4	03:36:28.47	-34:58:07.2	1199	57753	2.56 \pm 0.35	1.38 \pm 0.19
						+ 20	1.47 \pm 0.35	0.79 \pm 0.19
						+ 314	0.32 \pm 0.37	0.17 \pm 0.20
		S5	03:36:29.47	-34:57:25.3	1486	58067	1.22 \pm 0.24	0.66 \pm 0.13
						-294	-0.23 \pm 0.20	-0.13 \pm 0.11
NGC 1399	20.9	S1	03:38:27.75	-35:27:11.7	3693	56944	8.28 \pm 1.34	4.33 \pm 0.77
NGC 1404	20.2	S2	03:38:51.08	-35:35:17.8	2971	58079	6.18 \pm 0.52	3.02 \pm 0.25
NGC 4365	23.1	S1	12:24:28.01	+07:18:49.1	1199	57066	5.52 \pm 0.49	3.52 \pm 0.31
		S2	12:24:28.50	+07:19:33.5	1659	57066	4.31 \pm 0.41	2.77 \pm 0.26
		S3	12:24:29.41	+07:19:23.9	1804	57066	3.89 \pm 0.48	2.48 \pm 0.31
		S4	12:24:26.91	+07:18:53.5	1101	57066	2.60 \pm 0.42	1.66 \pm 0.27

$H\alpha/H\beta = 5-10$. The $H\beta$ line is clearly detected in NGC 1404-S1, however, with a ratio of ~ 3 , indicating little deviation from the Case-B value of 2.7. Novae are classified into Fe II and He/N spectral types, dependent on the strongest non-Balmer lines present, with the majority in the former class (Williams 1992). The NGC 1404-S1 spectrum cannot be classified confidently, but there is a hint that Fe II (42) could be present at low level, and blended Fe II (48,49) lines might contribute to the apparent broad flux excess at 5200–5400 Å.

The luminosity of NGC 1404, integrated over the region sampled by the discovery image, is $1.0 \times 10^{11} L_{\odot,K}$ (measured from 2 Micron All-Sky Survey Large Galaxy Atlas images; Jarrett et al. 2003). Hence, for a specific nova rate of $\nu_K \sim 2 \text{ yr}^{-1}$ ($10^{10} L_{\odot,K}$)⁻¹, there are ~ 20 eruptions per year.¹ For a typical $H\alpha$ decay rate of 0.03 mag d^{-1} (Ciardullo et al. 1990a), and assuming S1 was detected close to maximum, and could be confidently detected at 25 per cent of its observed flux, then the visibility period is $\sim 0.14 \text{ yr}$. Thus the mean number of detectable eruptions in the frame should be ~ 3 . Even allowing for the greater challenge of detection against the brightest parts of the continuum light, observing an ongoing nova in this frame (or indeed two novae, see Section 4) is not implausible.

3 X-RAYS AND RELATIONSHIP TO NGC 1404-X34

Novae are associated with ‘super-soft’ X-ray emission from the burning WD, which follows the optical outburst by tens to hundreds of days, when the ejected material becomes optically

thin to $\sim 0.5 \text{ keV}$ photons. A search for X-ray emission from NGC 1404-S1 yielded a $< 1 \text{ arcsec}$ match to NGC 1404-X34 in the *Chandra X-ray Observatory* source catalogue of Wang et al. (2016). NGC 1404-X34 was detected with a $0.3-8.0 \text{ keV}$ flux of $4.5 \times 10^{15} \text{ erg s}^{-1} \text{ cm}^{-2}$, corresponding to luminosity $2.2 \times 10^{38} \text{ erg s}^{-1}$ in a 45 ksec observation taken on 2003 May 28 (MJD 52788). However, it is absent from a 29 ksec observation on 2003 February 03 (105 d earlier), and from all other *Chandra* observations of NGC 1404. From its hardness ratios, the 2003 detection is categorized as a ‘quasi-soft source’, in the scheme of Di Stefano & Kong (2003).

Since the optical emission from novae precedes the X-rays, the 2003 *Chandra* detection does not relate to the 2017 outburst, but would have to be associated with a previous outburst, occurring 14 yr before to the MUSE observation. The X-ray luminosity of NGC 1404-X34 is close to the maximum expected in theoretical models of post-nova sources (Soraisam et al. 2016). Sources with such high luminosity require WDs close to the Chandrasekhar mass, and have higher effective temperatures ($kT \approx 100 \text{ eV}$) than lower luminosity systems, which would be in line with the ‘quasi-soft’ rather than ‘super-soft’ designation for NGC 1404-X34. Eruptions on the most massive WDs are also expected to have the shortest recurrence time-scales ($\lesssim 1 \text{ yr}$) and the briefest period of X-ray emission ($\lesssim 100 \text{ d}$) (Yaron et al. 2005). Such a short X-ray lifetime would be compatible with the appearance within 3 months in 2003, while frequent recurrence would be consistent with the NGC 1404-X34 in 2003 and S1 in 2017 being different (and not necessarily consecutive) eruptions of the same system. Such high-mass WD systems are predicted to be rare in ellipticals, however (Chen et al. 2016), and it may seem overly fortuitous to have observed the short-lived X-ray outburst.

The X-ray properties of NGC 1404-X34/S1 bear interesting comparison with nova M31N 2008-12a, which has the shortest known recurrence time (1 yr), and is also thought to be a massive

¹This calculation adopts the typical ν_K estimate from the ground-based searches with sparse time-sampling, where the detection biases may be comparable to those in the MUSE data.

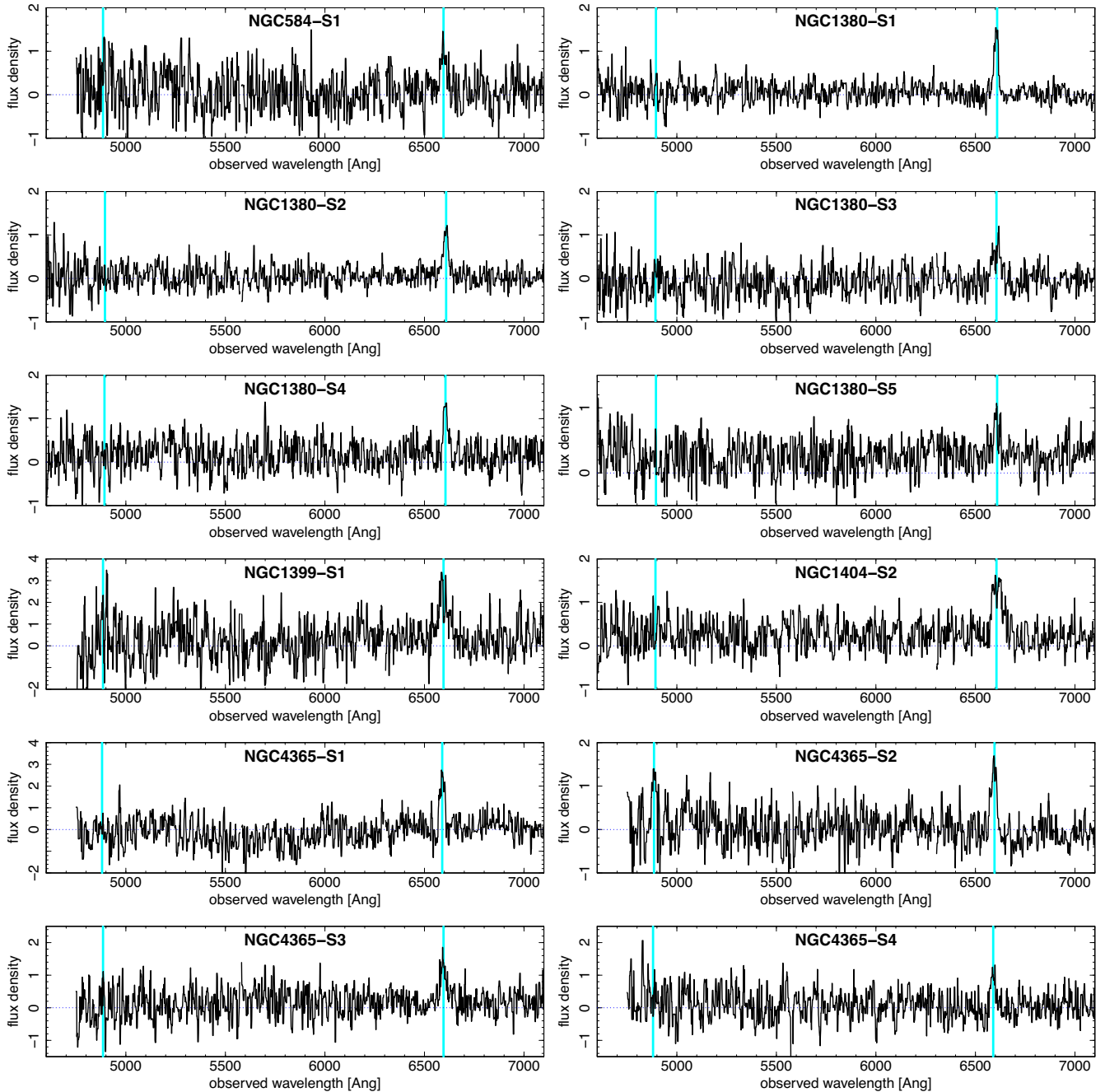


Figure 3. Additional nova candidates selected as broad- $H\alpha$ point sources in nearby early-type galaxies. The flux density unit is $10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$. For clarity only the 5-pixel smoothed spectra are shown. Cyan lines mark $H\alpha$ and the expected location of $H\beta$ (which is generally not detected).

WD accretor (Darnley et al. 2014; Henze et al. 2014; Tang et al. 2014), as well as one of the strongest candidates for a single-degenerate Type Ia supernova progenitor.

4 AN ARCHIVAL SEARCH FOR SIMILAR SOURCES

Motivated by the discovery of NGC 1404-S1, I have made a preliminary search for sources with similar properties in the MUSE archive. The goal here is not to generate a statistically robust sample, but simply to determine whether similar objects can be *routinely* detected in MUSE observations of nearby galaxies.

I searched for broad- $H\alpha$ point sources in MUSE data for 12 galaxies in total (NGC 584, NGC 1332, NGC 1380, NGC 1399, NGC 1404, NGC 1407, NGC 1428, NGC 3311, NGC 4374, NGC 4365, NGC 4473, and NGC 5419), selected to be nearby early-type galaxies having observations longer than 1800 s in the ESO archive as of December 2019, but excluding those with complex nebular $H\alpha$ emission (e.g. M 87). Overlapping observations separated by more than one night were treated separately. I made use of additional pointings in the outskirts of galaxies where available (e.g. NGC 1380 and NGC 1404), to enlarge the search area. From each datacube, I constructed net- $H\alpha$ emission-line images with bandwidths of 25 and 60 \AA (1100 and 2700 km s^{-1}), applied

a 2.5 arcsec FWHM unsharp-mask filter to suppress continuum-subtraction mismatch and any diffuse emission, and searched visually for spatially compact residuals. The spectrum of each candidate was then inspected to confirm that the line is broad. (A single bright narrow-line candidate was rejected, being likely a H II region or dwarf galaxy).

The archived MUSE data are nominally calibrated to a physical flux scale by the observatory pipeline. Most of the observations for the detected nova candidates were obtained during nights with stable photometric conditions (assessed from the seeing-monitor flux variation in the ESO database), and the flux calibration for these was adopted at face value. For one observation made in poorer conditions (NGC 4365), the photometric zero-point was checked independently against the *r*-band aperture flux of the galaxy from Sloan Digital Sky Survey imaging.

Table 1 and Fig. 3 show 12 additional nova candidate selected by this process, including a second source in NGC 1404, five in NGC 1380 (also in Fornax) and four in NGC 4365 (in the background of Virgo). In seven targets, no novae were detected. The range in detection number should not be taken to reflect a true difference in nova rate, given the small numbers and the absence of any corrections for variation in the extent and quality of the data.

The selected sources are characterized by the absence of bright lines other than H α , and little if any continuum emission. Apart from H α , the only convincing line detections are for H β in NGC 4365-S2 and for O I 8446 Å (beyond the spectral range shown in the figure) for NGC 1380-S1. Most of the sources are fainter than NGC 1404-S1, with luminosities in the range $(0.6\text{--}4) \times 10^{36} \text{ erg s}^{-1}$. The line widths are generally 1000–3000 km s $^{-1}$ FWHM, consistent with the bandwidths used in the selection process.

Multi-epoch data are available for five of the sources selected for broad H α emission (including NGC 1404-S1). In *all* of these cases, the line is absent in exposures taken >200 d before or after from the detection epoch; hence this selection method seems in general to yield transient sources. Disappearance on this time-scale is consistent with the H α fading rates of 0.01–0.08 mag d $^{-1}$ for M 31 novae Ciardullo et al. (1990b). In the case of NGC 1380-S4, three epochs are available. The H α line fades by a factor of 1.75 ± 0.50 in the 20 d between the first and second epoch, i.e. $0.030 \pm 0.015 \text{ mag d}^{-1}$. The third epoch is 294 d later and the emission is no longer detectable.

None of the additional sources has an X-ray counterpart in the Wang et al. (2016) catalogue.

5 SUMMARY AND OUTLOOK

The goal of this Letter has been to show that novae can be detected in typical MUSE observations of early-type galaxies out to ~ 20 Mpc.

Novae have been observed in such galaxies many times in the past, and H α -variability selection is a standard method for identifying them. To my knowledge, however, the current work is the first to detect novae at such distances in IFS data. The spectroscopic approach can provide more optimized tuning of the selection bandwidth, as well as improved continuum subtraction. Moreover, of course, the IFS method yields the full spectrum simultaneously.

Although the novae can be discovered in single observations, I have used multi-epoch data to help confirm their identification where available. Selecting *explicitly* for broad-H α variability would enable extension to galaxies such as M 87, which was excluded here due to confusion from its complex nebular H α emission. A possible future MUSE monitoring campaign observing with ~ 1 -

month cadence would be able to detect and follow $\gtrsim 20$ novae per target galaxy per year, while simultaneously building a very deep ‘static’ datacube that would find other applications, e.g. for detailed stellar populations and kinematic studies.

ACKNOWLEDGEMENTS

I thank Jay Strader for Twitter discussions which helped convince me that the sources were probably novae, John Lucey for comments on a draft version, and Michael Shara for very rapid peer review. This paper is based on data obtained from the ESO Science Archive Facility. The author was supported by the Science and Technology Facilities Council through the Durham Astronomy Consolidated Grant 2017–2020 (ST/P000541/1).

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